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Optimal dynamic expansion planning of distribution systems considering non-renewable distributed generation using a new heuristic double-stage optimization solution approach

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HIGHLIGHTS

- A dynamic expansion planning model for distribution system is presented.
- A new double-stage heuristic search-based optimization approach is proposed.
- A novel binary-to-integer transformation mechanism is suggested.
- The effectiveness of the proposed solution approach is extensively studied.

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ABSTRACT

This paper presents a dynamic (i.e., time-based) model for distribution system expansion planning (DSEP) considering distributed generation. The proposed model optimizes both investment and operation costs of distribution system. It determines the optimal location and size of distributed generators as well as the reinforcement strategy for primary (i.e., medium voltage) distribution feeders along a specified planning horizon. Besides, the dynamic feature of this model enables it to determine the time of each investment. The investment costs consist of installation cost of distributed generators and reinforcement cost of primary distribution feeders. Similarly, the operation costs comprise the cost of energy losses, operation and maintenance cost of the equipment and cost of power purchased from upstream grid (i.e., sub-transmission or transmission grid). The introduced model is solved using a combination of two efficient heuristic methods of Modified Integer-coded Harmony Search (MIHS) to find the optimal expansion scheme and Enhanced Gravitational Search Algorithm (EGSA) to optimize the operation costs. Furthermore, the suggested solution approach also incorporates an efficient mechanism for coding the candidate solutions in MIHS algorithm. The effectiveness of the proposed method and coding mechanism is extensively demonstrated by testing on two radial distribution systems and comparing the obtained results with the results of several other solution techniques.

1. Introduction

Distribution systems, as an electrical medium between high-voltage network and end users, have a critical and essential role in power systems. Distribution systems are commonly fed by sub-transmission or transmission substations including one or more high-voltage/medium-voltage transformers. Considering the loading limits of distribution system's facilities such as transformers, feeders, and breakers, and also the load growth of distribution systems, the distribution companies (DISCOs) have strong incentive to develop an appropriate strategy for expansion planning of their systems in order to provide the customers' demand with satisfactory level of quality and adequacy.

Considering numerous factors, such as deregulation of power market, significance of network's reliability and serious concern of global warming in recent years, DISCOs are willing to deploy the technology of distributed generation (DG) as an efficient and flexible option in distribution system expansion planning (DSEP). The DG technology is assigned to the application of a medium/small generator connected directly to medium-voltage/low-voltage (MV/LV) distribution systems [1–3]. Reduction of power losses, voltage profile improvement, postponing the time and expenditure for upgrading the existing

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Nomenclature

N_{LB}	number of load buses
N_{TB}	total number of system buses
NY	number of years of the planning horizon
N_{ll}	number of load levels of load duration curve (LDC)
LD_l	duration of load level l (h)
RDG	reserve capacity of DG (MW)
$CF_{r,i}$	reinforcement cost of the feeder feeding bus $i+1$ (U.S. \$/km)
$P^{DG}_{ins,i}$	installed capacity of DG in bus i (MW)
INV_{DG}	investment cost of DG (U.S. \$/MW)
OMC_{DG}	operation and maintenance cost of DG (U.S. \$/MW h)
$UP_{t,l}$	purchased active power from the upstream grid in load level l of year t (MW)
$UQ_{t,l}$	reactive power injected from the upstream grid in load level l of year t, i.e. the reactive power corresponding to $UP_{t,l}$ (MVAR)
$SP_{t,l}$	system demand in load level l of year t (MW)
$EP_{t,l}$	electrical Energy price in load level l of year t (U.S. \$/MW h)
$P^{DG}_{i,t,l}$	active power output of DG in bus i and load level l of year t (MW)
$Q^{DG}_{i,t,l}$	reactive power output of DG in bus i and load level l of year t (MVAR)
$Ploss_{t,l}$	power loss of primary distribution system in load level l of year t (MW)
$V_{i,t,l}$	voltage of bus i in load level l of year t (p.u.)
$\lvert\cdot\rvert$	a function that returns the magnitude of its complex argument
$I_{ij}(t,l)$	current of the feeder between bus i and bus j in load level l of year t (in amperes)
dr	discount rate
$\tau(t)$	net present value transforming function as $1/(1+dr)^t$
$H(x)$	heaviside unit step function: $H(x)=1$ if $x>0$ and $H(x)=0$ if $x\leqslant 0$
$Rf(\cdot)$	a function that returns the real part of its complex argument
$\mu_{DG,i}$	binary variable representing status of DG at bus i (1 = installed, 0 = not installed)
$\mu_{R,i}$	binary variable representing reinforcement status of the feeder feeding bus $i+1$, which is also known as immediate feeder of bus $i+1$ (1 = reinforced, 0 = not reinforced)
$IY_{DG,i}$	installation year of DG at bus i ($1\leqslant IY_{DG,i}\leqslant NY$)
RY_i	reinforcement year of the feeder feeding bus $i+1$ ($1\leqslant RY_i\leqslant NY$)
$P^{dem}_{i,t,l}$	active power demand of bus i in load level l of year t (MW)
$Q^{dem}_{i,t,l}$	reactive power demand of bus i in load level l of year t (MVAR)
AD_{ij}	admittance of feeder between bus i and j (p.u.)
$\theta_{i,t,l}$	phase of voltage at bus i and load level l of year t
δ_{ij}	phase of admittance between bus i and bus j
V^{min}	lower limit of voltage (p.u.)
$V^{\max}$	upper limit of voltage (p.u.)
$S_{i,t,l}$	apparent power flow of the feeder feeding bus i in load level l of year t (MVA)
$S_i^{\max}$	maximum capacity (thermal rating) of ith primary feeder (MVA)
N_b	number of binary variables of the equivalent binary form of each DDSEP candidate solution
NI	number of integer variables of the equivalent integer form of each DDSEP candidate solution
HV_i^{It}	ith HV in iteration It
VEL_i^{Iter}	velocity of mass i in iteration $Iter$
CX_i^{Iter}	position of individual (mass) i in iteration $Iter$
CX_{best}^{Iter}	best position of the GSA population's individuals in iteration Iter
CX_{worst}^{Iter}	worst position of the GSA population's individuals in iteration Iter
GM_i^{Iter}	gravitational mass for individual i in iteration $Iter$
$GF_{i,q}^{Iter}$	gravitational force applied to mass i by mass q in iteration $Iter$
$ED_{i,q}^{Iter}$	Euclidean distance between mass i and mass q in iteration $Iter$
$G(Iter)$	gravitational constant in iteration $Iter$
G_0	initial value of gravitational constant
TF_i^{Iter}	total gravitational force applied to mass i in iteration $Iter$
MAC_i^{Iter}	acceleration of mass i in iteration $Iter$
ρ_1	weighting coefficient for acceleration of mass i in the proposed EGSA
ρ_2	weighting coefficient for P_{best} of mass i in the proposed EGSA
$P_{best,i}^{Iter}$	the best position of individual i obtained up to iteration $Iter$

distribution system, lower financial risk, short time interval of construction are among some technical and economical advantages of DG in distribution systems [4–6]. Nevertheless, all the mentioned advantages basically depend on location, size, technology (e.g., renewable or non-renewable) and operation mode of DGs. Application of high DG capacity without reasonable and optimal exploitation planning may result in some molesting problems, such as power losses' escalation, power quality degradation, and protection disturbance [7]. For this reason, diverse models and solution approaches have been presented in recent years addressing the DG inclusion in DSEP problem. These models comprise a broad range of objectives such as power losses' reduction, voltage profile improvement, investment deferral in network upgrading, reliability improvement as reduction of energy-not-supplied (ENS), and reduction in cost of purchased power from upstream grid for serving the customers. Furthermore, different solution approaches have been used to solve these models. In [8], a modified particle swarm optimization as a solution method for the multistage distribution expansion planning problem considering dispatchable DGs and storage modules is proposed. Their model minimizes the investment, operation and reliability costs as the objective function. In [9], a dynamic multi-objective planning model is proposed for distribution system expansion including DGs. By solving the model with a hybrid heuristic solution approach, i.e. immune genetic algorithm (IGA), the optimal expansion scheme is determined. In [10], a multi-objective multi-stage DSEP model in presence of DG is suggested. A similar model is presented in [11] with the aim of minimizing the costs related to investment, operation and reliability. In [12], a heuristic approach based on back-propagation algorithm combined with cost-benefit analysis is introduced to solve the multi-year expansion model of distribution system planning. The model of [12] determines the optimal placement, sizing and timing of DG installation as well as distribution system's reinforcement. Investment, reliability and losses' costs are taken into account in [13] as the objectives to be minimized in a time-based DSEP framework. Both DG planning and network's reinforcement strategy are considered in the model of [13]. In [14], a dynamic model for DSEP, with the aim